Self-Diagnosis and Self-Planning with Constraint-based Hybrid Models

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1 INTRODUCTION

Many of today's embedded systems – such as automobiles, automated factories or chemical plants – are an increasingly complex mixture of hardware components and embedded control software, showing both continuous (vehicle dynamics, silo fill levels) and discrete (software) behavior. As complexity grows, handling such systems, e.g. diagnosing and repairing faults, becomes harder. This problem is addressed by model-based reasoning, which enhances these systems with self-diagnosis and self-planning capabilities based on Hidden Markov Models (HMMs) of their structure and behavior. At the heart of these capabilities are the problems of estimating the internal state and automatically plan intelligent control (re)actions. However, HMMs cannot model continuous behavior.

In my thesis, I address the stated problems for *hybrid systems* with an integrated approach combining concepts from AI (constraint optimization, HMM reasoning), fault diagnosis in hybrid systems (stochastic abstraction of continuous behavior), and hybrid systems verification (hybrid automata).

2 PROBLEM: STATE ESTIMATION AND PLANNING FOR HYBRID SYSTEMS

Computing internal states is the well known problem of *belief state estimation*, which is to compute a probability distribution over all system states. The problem of reactive planning when facing contingencies is to find suitable actions that most probably achieve a given goal. The first challenge lies in addressing these problems for hybrid models of (uncertain) system behavior, which allow uncountable many trajectories. The second challenge are the very limited resources in embedded systems. In my thesis, I aim to address these challenges by contributing 1) a modeling formalism with hybrid-to-discrete model abstraction 2) an approach based on *soft-constraint optimization* (Dechter, 2003) which collapses the problems of diagnosis and planning into the single problem of computing the most probable trajectories, i.e. sequences of system states, which are consistent with partial observations and which entail given goals and 3) a fast and flexible approximation via *adaptive abstraction*.

State-of-the-art hybrid diagnosis (Lunze and Nixdorf, 2001; Hofbaur and Williams, 2002) generally uses algorithms tailored to modeling formalisms. In contrast, I will use generic soft-constraint optimization algorithms, implemented in optimized off-the-shelf solvers such as toulbar2[1]. The resulting deeper separation of concerns then allows for quick integration of new developments, while model-specific features may be exploited via custom heuristics.

I will bridge the gap between continuous behavior (hybrid systems world) and qualitative reasoning (AI world, soft-constraint optimization) using conservative *adaptive abstraction*. System states are aggregated into abstract states and discrete state transitions mapped to probabilistic ones, while ensuring that an abstract state/transition always receives the upper bound of probabilities of aggregated states/transitions. The number of aggregated states/transitions is automatically adapted to resource limits. The first step is the hybrid-to-discrete abstraction, resulting in a model encoded with soft-constraints. They encode preferences for discrete model variable assignments, thereby representing system states and probabilistic state transitions. The next step is an abstraction hierarchy of increasingly refined abstract constraints, similar to (Koster, 1999, Chapter 4). Solutions of higher abstraction levels then guide heuristic search on lower levels.

3 RESEARCH PLAN

My thesis plan consists of four roughly successive parts. The main tasks in Part 1 are to create experimental real-world (RW) models, develop a hybrid model formalism and develop needed tools, e.g., for automatic model-abstraction. These tasks are strongly interdependent. Further tasks are to define constraint-based abstraction based on the known method of *domain abstraction* (i.e. how to generate abstract from concrete constraints), define an architecture for tools and components (e.g. model abstraction), evaluate existing tools (e.g. the hybrid verification tool PHAVer[2])

[1] https://mulcyber.toulouse.inra.fr/projects/toulbar2/

[2] http://www-verimag.imag.fr/~frehse/phaver_web/index.html

and run preliminary experiments.

Part 2 mainly consists of developing a hybrid diagnosis and planning component by collaborating with the *cognitive factory* project(Buss *et al.*, 2007). Further tasks are to generalize constraint-based abstraction beyond domain abstraction, define iterative refinement for COP, create bigger RW models and refine the hybrid model formalism.

Part 3 consists of testing different COP algorithms and developing new ones, e.g. to incorporate abstraction. Finally, in Part 4, algorithms are thoroughly analyzed experimentally and theoretically and the COP approach is compared against other problem solving formalisms, e.g. weighted SAT. Another idea is to generate heuristics for COP algorithms which allow to exploit, e.g., by-design refined model structure.

On a time line, part 1 takes one and a half years, which is roughly up to now, part 2 one year and part 3 and 4 together one and a half years.

4 PROGRESS TO DATE

Part 1 is mostly done, the tools need some further refinement. Based on Probabilistic Hierarchical Constraint Automata (PHCA), a compact encoding of HMMs for flexible embedded design (Williams *et al.*, 2001) I developed Hybrid PHCAs (HyPHCAs) in style of Hybrid Automata (Henzinger, 1996). They extend the PHCA capability to model uncertain hardware as well as complex software behavior with continuous modeling using *linear Ordinary Differential Equations* (ODEs). To achieve tractability, I developed a discretization tool which implements a well known conservative, stochastic approximation of continuous state evolution using Markov chains (Lunze and Nixdorf, 2001). The result is an abstracted, purely discrete model.

We recently submitted a paper to the PHM conference introducing HyPHCAs and describing how the problem of computing most probable trajectories is formulated as a Constraint Optimization Problem (COP) (Dechter, 2003). The discrete model is encoded as soft-constraints, unfolding its execution over N time steps. The k-best solutions to the COP are the k most probable trajectories, which explain partial observations (e.g., with fault modes) and entail goal-achieving commands. Part of this work are preliminary experiments on an RW model of a filling station, consisting of a silo and a sensor. COPs with ≈ 840 variables and ≈ 920 constraints were generated from a hybrid model and solved within tenth of seconds, showing the method's feasibility. In (Maier *et al.*, 2009) we introduce a model-based capability for the cognitive factory which integrates COP-based *plan assessment* with diagnosis. It is weaker than full planning and diagnosis, evaluating the success probability of a *given* production plan. Constraint-based abstraction is addressed in (Maier and Sachenbacher, 2008): we introduced a soft-constraint algorithm which adapts the size of variable domains to given resource limits. It is based on *domain abstraction*, which combines variable values to reduce its domain size (and thus the overall problem size). We ran preliminary experiments with it on a satellite diagnosis problem with 73 variables (domain sizes 2-6) and 45 constraints. The next steps are to develop a clear semantics of HyPHCAs and their discrete abstraction and start development of the hybrid diagnosis and planning component.

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